

TEMPERATURE AND HARD X-RAY SIGNATURES FOR ENERGETIC PROTON EVENTS

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ABSTRACT

The temperature distributions of flares associated with solar energetic protons (SEPs) have been found to differ significantly from those of normal (non-SEP-associated) flares. At high temperature (≥ 20 MK) and high X-ray intensity, the two temperature distributions merge. At lower temperature ($\lesssim 20$ MK) and low X-ray intensity, the distributions separate; the SEP-associated flares tend to exhibit temperatures anomalously lower than those of normal flares. At high X-ray intensity, gradual hard X-ray flares are highly correlated with SEPs; at low-to-moderate X-ray intensities, this correlation is much weaker. These two properties, a low-temperature signature for weak flares and a gradual hard X-ray signature for intense flares, may prove useful in identifying events potentially productive of SEPs for all levels of intensity above soft X-ray class M1.

Subject headings: Sun: flares — Sun: particle emission — Sun: X-rays, gamma rays

1. INTRODUCTION

Large concentrations of solar energetic protons (SEPs), propagating through the interplanetary medium, have been found to disrupt many technological systems in space and on Earth. Much research has been devoted to early detection, identifying signatures of SEP acceleration in flares and other possible precursors on the Sun (Heckman, Kunches, & Allen 1992).

A recent study of flare-maximum temperatures, calculated from broad-band soft X-ray measurements (Garcia & McIntosh 1992), suggested a temperature dependence (discussed in § 2 of this paper) that distinguishes flares associated with SEPs from flares that are not. The current study also suggests that low temperatures and gradual hard X-ray bursts may originate from a common species of flare. (Hereafter in this paper, SEP-related flares are referred to as “SEP flares,” and non-SEP-related flares are called “normal flares.”)

The correlation between SEPs and an uncommon type of flare characterized by progressively hardening spectra in hard X-rays (Bai 1986; Cliver et al. 1986a) appears to be useful in the early detection of SEPs. Progressive spectral hardening usually follows the flare’s early impulsive phase by significant time intervals, generally less than 5 minutes (A. Kiplinger, private communication) but sometimes as long as 60 minutes. Since high-energy protons can be observed in the magnetosphere within an hour of soft X-ray maximum for west-meridian flares, the identifying hard X-ray signature and the particle event onset could be almost concurrent. However, the initial particle enhancement is not sufficient in itself to qualify as a criterion for event detection; therefore, the progressive spectral hardening signature remains a useful and important diagnostic.

The following section presents evidence that SEP-related flares are temperature dependent and discusses methods of exploiting this dependence as a diagnostic for the early detection of SEPs. Section 3 explores the statistical empirical relation of gradual hard X-ray flares to SEPs. Section 4 compares the correlative and anticorrelative relationships of SEPs to other manifestations of gradual and impulsive flares; it also shows whether these phenomena can have close and possibly exploitable association with SEPs. Section 5 describes the gradual hard X-ray flare and suggests a physical interpretation for the empirical SEP associations. The final section summarizes the results of this study and discusses the questions raised by those results.

2. EVIDENCE FOR ANOMALOUS TEMPERATURE DEPENDENCE OF SEP FLARES

SEP events are associated with flares of widely varying intensity (Kunches 1991, private communication; Cliver et al. 1989; Cliver & Cane 1989; Kahler et al. 1984; Nonnast, Armstrong, & Kohl 1982; Shea & Smart 1990). NOAA’s Space Environment Services Center (SESC) uses the following criterion for SEP events: ≥ 10 particles $\text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1}$ for ≥ 10 MeV protons sustained for ≥ 15 minutes. (The background level for the *GOES* proton detectors is ~ 0.1 particles $\text{cm}^2 \text{sr}^{-1} \text{s}^{-1}$, so many more SEPs are registered than are reported.) Cliver et al. (1989) used lower threshold criteria than does SESC for detecting SEPs, but Cliver & Cane (1989) and Shea & Smart (1990) used criteria identical to SESC’s. SESC’s criterion is practical because this flux intensity also represents the approximate threshold of terrestrial significance. Selection criteria for SEP-associated flares are described in more detail in § 3.

Figure 1 shows a scatter plot of maximum flare temperature versus log maximum X-ray flux. Normal flares are shown as dots, SEP flares by open circles, and ground-level events (GLEs)—caused by GeV-energy solar protons—by solid circles. This data set extends from 1977 September to 1991 May. However, it is not homogeneous: few moderate-to-weak normal flares ($\leq M8$) are included before 1984; flares from 1984 May to 1988 September are mostly SEP flares; but from 1988 September to 1991 July, both normal and SEP-type $\geq M1$ flares have been included. It would have been very difficult to access the archival data for the large number of small flares from 1977 to 1988. From 1988 forward, networking facilities made this task more practical on a near real-time basis. The method for computing temperatures (and emission measures) from *GOES* broad-band X-ray data is described by Garcia (1993).

Although the data contain few normal less than M8 flares before 1984, many moderate ($\geq M4$) SEP flares were included for that period. Consequently, SEP flares are, in general, better represented throughout the above epoch; more low-intensity normal flares in the early period would have increased the density of that portion of the distribution but probably would not have altered the final results significantly.

A least-squares analysis determined the principal axis (represented by a straight line in Fig. 1) of each distribution, in which SEPs and GLEs were treated as one. This analysis fitted

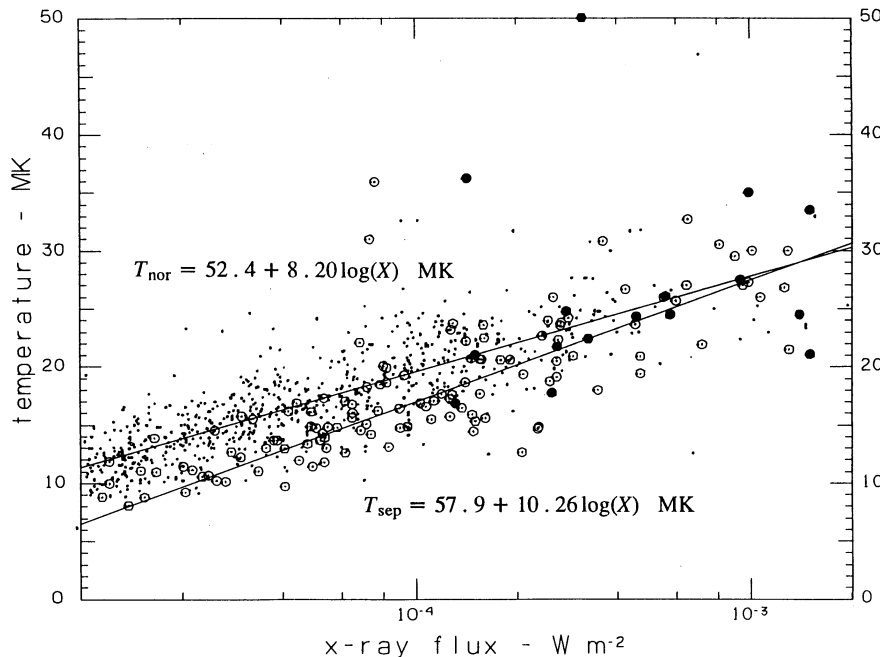


FIG. 1.—Scatter plot for solar energetic proton (SEP) flare and normal (non-SEP) flare temperatures vs. maximum (log) soft X-ray flux intensity. The dots represent normal flares, open circles SEP flares, and solid circles ground-level events (GLEs). The upper solid line is the principal axis of the normal flare temperature distribution. The lower solid line is the SEP-flare temperature distribution.

two parameters for each distribution: the temperature at X-ray intensity M1 and the slope of temperature versus log X-ray intensity variation. The distribution envelope for each flare population is seen to increase monotonically with X-ray flux intensity, but with different slopes: 10.2 MK per 10-fold increase in power (W m^{-2}) for SEP flares, and 8.2 MK per 10-fold increase for normal flares.

Normal flares and SEP flares have, on average, different temperature distributions. These distributions overlap at high temperature (and high X-ray intensity), but diverge at low temperature (and low X-ray intensity). At high X-ray intensities, SEP flares account for a disproportionate number of high- as well as low-temperature flares. In a recent study of high-temperature flares Garcia & McIntosh (1992) found that, for the most intense flares, the highest temperature flares were SEP flares. In other words, SEP flares occupy both the high-temperature and low-temperature extremes for high-intensity $> \text{X2}$ flares. Consequently, high temperature does not exclude the possibility of SEP flares; other corroborating factors are needed.

2.1. A *t*-Test for Possible Temperature Distribution Differences between SEP Flares and Normal Flares

To demonstrate quantitatively that SEP flares have a different temperature distribution from that of normal flares, a *t*-test was performed, treating small intervals of X-ray flux independently. Table 1 contains the main results of these tests over eight X-ray flux intervals (factors of $2 \times 10^{-5} \text{ W m}^{-2}$ up to 1×10^{-4} , then factors of $2 \times 10^{-4} \text{ W m}^{-2}$ up to 6×10^{-4} . [The *t*-test determines the confidence level of the hypothesis that the two populations (SEP flares and normal flares) have the same mean ($\mu_1 = \mu_2$) temperature within each flux range tested. The extent to which this hypothesis has been upheld is demonstrated by the significance level *P*.]

The lowest flux ranges, 1–3 (X-ray flare classes M1–M2,

M2–M4, M4–M6), indicate that the *P*-values associated with the *t*-test are quite small. (For ranges 2–3, *P* is less than the stipulated threshold of 0.00001). Range 4 (M6–M8 flares) indicates that there is no significant difference in the mean temperatures of the two populations; however, the next two X-ray flux ranges (M8–X1 and X1–X2) suggest that the temperature distributions are still significant. From X2 to X6 there are no significant differences in the temperature means of the two populations. Above X6 the data are insufficient to allow statistical tests.

2.2. A Probability Model for SEP Flares

The distribution of SEP flares with respect to maximum temperature and maximum X-ray flux shows two outstanding characteristics: (1) a negative temperature gradient at low X-ray intensities and (2) a quasi-null temperature gradient at high X-ray intensities. For forecasting purposes, it will be convenient to be able to express the expected probability, *P*, of an SEP event by a simple formula that is dependent only on

TABLE 1
RESULTS OF *t*-TEST TEMPERATURE DISTRIBUTION DIFFERENCES
BETWEEN SEP FLARES AND NORMAL FLARES^a

Range	Flux Range (W m^{-2})	<i>P</i>	<i>t</i>	DOF ^b
1.....	$1-2 \times 10^{-5}$	0.015	2.47	164
2.....	$2-4 \times 10^{-5}$	<0.00001	4.57	304
3.....	$4-6 \times 10^{-5}$	<0.00001	4.33	103
4.....	$6-8 \times 10^{-5}$	0.519	0.65	68
5.....	$8-10 \times 10^{-5}$	0.028	2.25	59
6.....	$1-2 \times 10^{-4}$	0.014	2.49	136
7.....	$2-4 \times 10^{-4}$	0.352	0.94	72
8.....	$4-6 \times 10^{-4}$	0.349	0.96	19

^a Statistical data provided by C. Wang 1992.

^b DOF = degrees of freedom.

observed maximum X-ray flux, X , observed maximum temperature, T , and heliographic longitude, θ . Moreover, a mathematical expression that emulates the empirical relationships between SEP incidence, X , and T should also help to illuminate the underlying physical processes.

The production of interplanetary energetic protons may in some way be a continuous function of X and T , but the empirical results with which we must work provide only binary responses; i.e., either an SEP was observed at the threshold level of the particle detector or none was observed following a flare. A statistical analysis known as *logistic regression* is appropriate for observational studies where each event, characterized by a binary result, is associated with a set of explanatory variables (in this case, X and T).

Customarily, linear models are used to evaluate empirical data where observed outcomes are shown to be dependent in some unknown way upon a set of observed environmental variables:

$$\eta = \sum_{j=1}^p x_j \beta_j, \quad (1)$$

where x is an observed vector of independent variables, β is a vector of unknown coefficients and $-\infty < \eta < \infty$. However, the expression of probability, P , as a linear combination such as in equation (1) would be inconsistent with the laws of probability. Therefore, a link function, $g(P)$ is needed; it maps the unit probability interval (0, 1) onto the real function, η :

$$g(P_i) = \eta_i = \sum_{j=1}^p x_{ij} \beta_j, \quad i = 1, 2, \dots, n. \quad (2)$$

In this case, the logit function

$$g(P) = \ln [P/(1 - P)] \quad (3)$$

is used (McCullagh & Nelder 1983). The functional relationship between P and η becomes

$$P[\log(X), T, \theta] = \frac{e^\eta}{1 + e^\eta}. \quad (4)$$

In this model we have used five terms; these include (in addition to the X and T terms) a constant term, an interaction between X and T , and a term that accounts for the dependence of SEP incidence on heliographic longitude, θ . The data consisting of binary responses spanning the X , T , θ space yielded the following model:

$$\eta = 12.2558 + 1.980 \log(X) + 0.2049T + 0.1286 \log(X)T - 1.5684 \begin{cases} 1 & > \text{E40} \\ 0 & < \text{E40} \end{cases}, \quad (5)$$

where X is W m^{-2} , T is MK, and the heliographic longitude (θ) dependence has the form of a delta function (1 if θ is east of E40° and 0 if θ is west of E40°).

The “goodness” of this model was estimated by computing the standard deviation of the difference between the continuous function $P[\log(X)T, \theta]$ and the binary occurrence of SEPs in the sample shown in Figure 2. This estimated standard deviation is $\sigma = 0.098$.

In formulating the coefficients of equation (5), the heliographic longitude dependence was invoked as shown; however, this term has an ad hoc dependence on individual events; it is not useful for displaying the continuous probability prediction function, which is dependent only on $\log(X)$ and T . Figure 2 superposes probability contours computed from equations (4) and (5)—excluding the final term—over the data sets shown in Figure 1 (also used in the parameterization process).

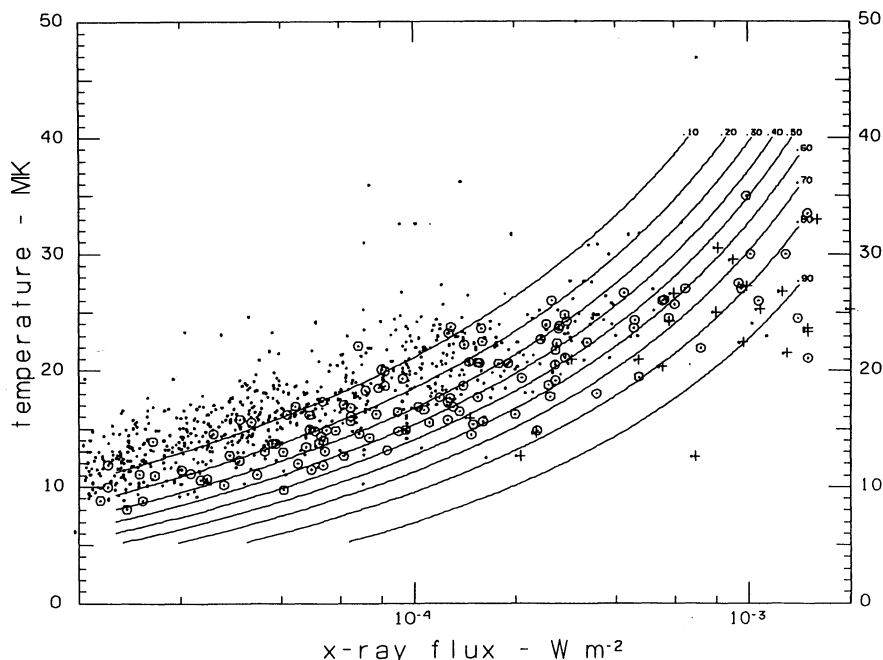


FIG. 2.—Probability contours from $P = 0.1$ to $P = 0.9$, computed by the model described in the text, are superposed over the same SEP flare (open circles) and non-SEP flare (dots) data shown in Fig. 1. Non-SEP flares at heliographic longitudes east of E40° are marked by crosses in regions where the computed probability is greater than 0.5. GLEs that were not also SEPs were not included in this analysis.

The probability prediction function accommodates both a diminishing SEP dependence on temperature at large X-ray intensities and a significant temperature dependence at small X-ray intensities. A significant number of non-SEP events are located in the triangular high-probability zone bounded roughly by $X = 10^{-4} \text{ W m}^{-2}$, $T = 12 \text{ MK}$, and $X = 2 \times 10^{-3}$, $T = 38 \text{ MK}$, and $X = 2 \times 10^{-3}$ and $T = 12 \text{ MK}$. However, most of these occurred at large eastern central meridian distance (CMD). Those non-SEP events at heliographic longitude east of $E40^\circ$ and the estimated $P \geq 0.5$ are marked by crosses. There were 20 non-SEPs east of $E40^\circ$ and 13 non-SEPs west of $E40^\circ$ in this zone. In zones of higher probability, the effect of large eastern longitude is even more pronounced; e.g., for $P \geq 0.8$ there were 11 events of $E40^\circ$ and only two events west of $E40^\circ$. This result suggests that in regions of high SEP probability the SEP was not observed at Earth because of the unfavorable magnetic connectivity between Earth and the flare site on the Sun.

2.3. Temperature Dependence of Gradual Hard X-Ray Flares

The fact that populations of SEP flares and normal flares have different temperature dependences suggests that at least two distinctly different flare types are involved. Because the temperature dependences have different slopes, and the temperature distribution for intense SEP flares includes both very high temperature flares as well as very low temperature flares, the interpretation of high-intensity SEP flares is much more difficult. Because other indicators (see below) suggest that SEPs are related to gradual X-ray flares, and more specifically to gradual hard X-ray (GHX) flares, it is useful to look for temperature dependence in GHX flares. In this study, GHX flares were obtained from the combined rosters of Bai (1986) and Cliver et al. (1986a). Bai's (1986) Table 3 contained 23 events, the Cliver et al. (1986a) list contained 10 events, and three events were common to both sets. The selection criteria from the two groups was slightly different. Bai (1986) identified

GHX flares on the basis of the following criteria: (1) long duration (> 10 minutes) in hard X-rays; (2) > 1.5 minute duration of the strongest hard X-ray burst; (3) gradual behavior at the largest hard X-ray spike bursts; (4) high microwave richness index, mostly greater than 3.5; (5) effective peak rate of about $1000 \text{ counts s}^{-1}$.

Bai found the following common characteristics at gradual flares: (1) gradual light curves; (2) ≥ 12 minute duration of the whole hard X-ray flare; (3) spectrum that hardens with time; (4) flat hard X-ray spectra.

Cliver et al. (1986a) identified eight GHX flares from Ottawa and Penticton 2.8 GHz data; these events were selected on the basis of a microwave burst component with (1) greater than 10 minute FWHM duration; (2) peak intensity of greater than 250 solar flux units (sfu) ($1 \text{ sfu} = 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$); (3) and relatively smooth in their time profiles.

Cliver et al. (1986a) also selected two other events that were not observed by Ottawa or Penticton but satisfied the above criteria.

The selection criteria of both Bai and Cliver included long-duration and relatively intense flares. Despite the differences in selection criteria, both groups found similar characteristics in the GHX flares (see § 4).

Figure 3 contains a scatter plot similar to Figure 1. In this case GHX events are also marked, by circles, against a background of the more common impulsive hard X-ray (IHX) flares (shown as dots). (The straight solid line is the axis of the normal flare distribution from Fig. 1, shown for reference purposes.) This data set spans 1980–1982 for both flare populations (since the GHX set was collected for that period). In this plot, the tendency to lower temperatures for GHX flares is notable, but not as prominent as in the case of SEP flares (Fig. 1). Approximately twice as many GHX flares (19) fell below the normal flare axis as fell above it (9).

A t -test was also performed on the GHX versus normal flare data sets (Table 2). The same flux ranges were used as for the

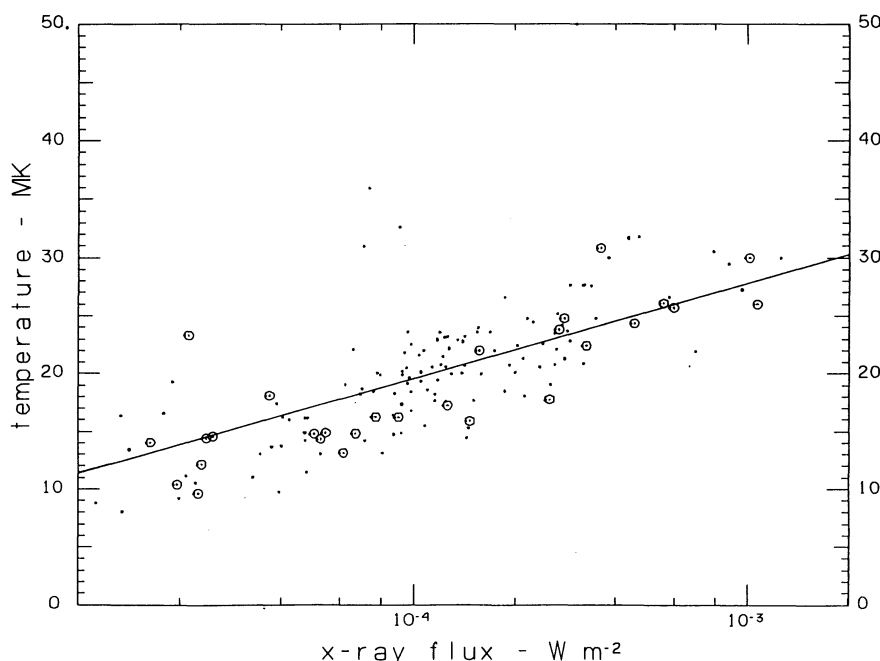


FIG. 3.—Scatter plot of gradual hard X-ray (GHX) flares and normal (non-GHX) flare temperatures vs. maximum soft X-ray flux intensity. Dots represent normal flares, and open circles represent GHX flares. The linear normal flare temperature distribution from Fig. 1 is shown, for reference, as a solid line.

TABLE 2

RESULTS OF A *t*-TEST FOR TEMPERATURE DISTRIBUTION DIFFERENCES, BY X-RAY INTERVALS, BETWEEN GHX FLARES AND NORMAL FLARES

PARAMETER	FLUX RANGE (W m^{-2})						
	$1\text{--}2 \times 10^{-5}$	$2\text{--}4 \times 10^{-5}$	$4\text{--}6 \times 10^{-5}$	$6\text{--}8 \times 10^{-5}$	$8\text{--}10 \times 10^{-5}$	$1\text{--}2 \times 10^{-4}$	$2\text{--}4 \times 10^{-4}$
P	0.29	0.87	0.62	0.35	0.34	0.03	0.86
$\bar{T}_{\text{GHX}}(\text{MK})$	12.2	15.3	14.6	14.7	16.2	18.4	23.9
$\bar{T}_{\text{NOR}}(\text{MK})$	15.0	15.8	15.0	17.0	20.8	20.8	23.8

SEP *t*-test; however, the paucity of data for this short time interval diluted the statistical significance of this analysis. Despite this shortcoming, the mean temperatures of GHX flares were consistently lower (with one marginal exception) than those of the normal flares. There were, essentially, no data for flux greater than $6 \times 10^{-4} \text{ W m}^{-2}$.

Finally, a *t*-test was performed for the full range of X-ray flux; this test yielded a statistically significant probability that the GHX flares and normal flares have different temperature distributions. In this case,

$$\begin{aligned}
 P &= 0.057, \\
 \bar{T}_{\text{SEP}} &= 18.8 \text{ MK}, \\
 \bar{T}_{\text{NOR}} &= 20.87 \text{ MK}.
 \end{aligned}$$

SEP incidence, prevalent among both low-temperature flares (LTFs) and GHXs, is not the only common denominator connecting these phenonema. Both LTFs and GHXs exhibit the well-known characteristics of long-duration events (LDE); viz., smoothness in the light curve; slow rise to maximum and extended gradual decays; and long-period soft X-ray enhancements.

To demonstrate that both SEP and GHX flares are also LDE flares, Figure 4 contains a plot of soft X-ray flare dura-

tions at the full wave, half-maximum (FWHM) X-ray intensity level versus the normalized flare temperature for the 1976–1986 epoch. In this application, flare temperatures are normalized by dividing the observed soft X-ray color temperature by the average temperature of a normal (non-SEP) flare at the level of X-ray intensity, computed from the distribution function

$$T_{\text{nor}} = 52.4 + 8.20 \log(X) \text{ MK} . \tag{6}$$

The normalized flare temperature derived in this manner was used because the expected maximum temperature increases, on average, in proportion to the logarithmic maximum X-ray intensity as shown in Figure 1. In Figure 4, SEP flares are indicated by circled asterisks, GHX flares by filled circles, and normal flares by plain asterisks. It is clear normal flares have short FWHM durations; SEP and GHX flares have longer durations; and the majority of SEP and GHX events are LTF, i.e., have normalized temperatures less than 1.

3. EVIDENCE FOR GRADUAL HARD X-RAY FLARE-SEP DEPENDENCE

The relationship of GHX flares and SEPs is important because, as a medium for predicting SEPs from large flares, it complements the low-temperature pattern of weaker flares. The association between GHX flares and SEPs has been

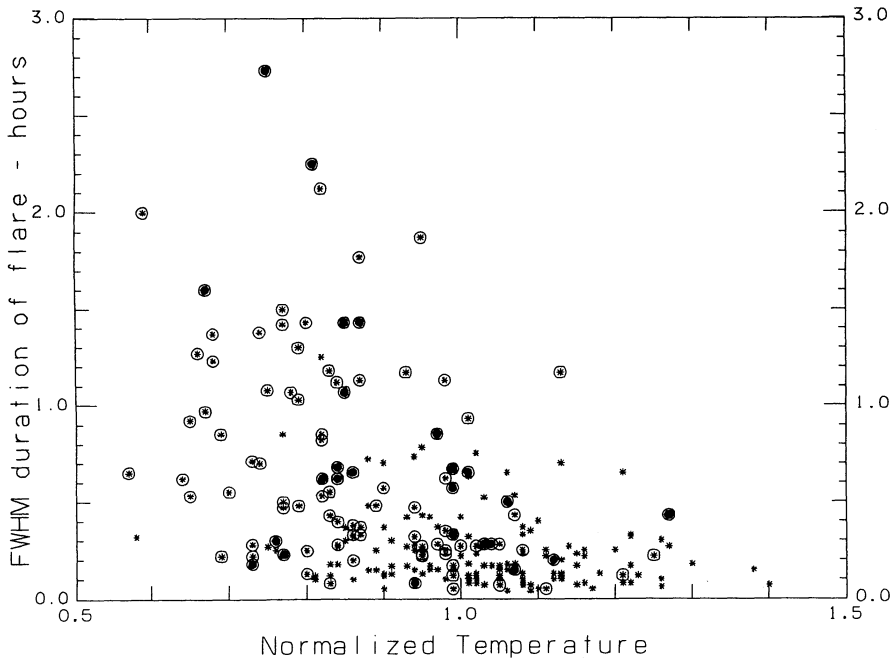


FIG. 4.—Scatter plot for flare durations at the FWHM level of maximum X-ray intensity vs. normalized maximum flare temperature, described in the text. SEP events are indicated by circled asterisks, GHX events by filled circles, and normal (non-SEP) flares by plain asterisks.

examined by at least two authors: Bai (1986) and A. Kiplinger (private communication); thus it is known that SEPs often follow GHX flares. In this section I shall consider the importance of intensity and heliographic position in this relationship.

The conjunction of GHXs with SEPs may be viewed either from the perspective of the geospace forecaster (that an SEP will follow a GHX flare) or in the opposing context (that a GHX flare will result in an SEP). The former case is considered here because it is possible that an SEP may occur in the absence of an observed GHX; the latter case has been subordinated because the failure of an observed GHX to predict an SEP results only in a false alarm.

Several data sources were used to test the efficacy of GHX identification in forecasting the occurrence of SEPs. A list of intense SEPs was obtained from SESC; these events were qualified as SEPs according to SESC criteria (see § 2). Additional lists of SEPs (which also include many SESC-qualified SEPs) were reported by Cliver et al. (1989), Cliver & Cane (1989), and Shea & Smart (1990).

Shea & Smart (1990) and Cliver & Cane (1989) used the same basic selection criteria for their event list as SESC does but considered significant flux enhancements following the onset of a long period of high-level particle flux as separate events. SESC considers the original event as a single entity, encompassing all subsequent peaks until the overall flux returns to pre-event levels. The Shea & Smart (1990) list contains more than 200 proton events from 1955 through 1986.

The Cliver & Cane (1989), Cliver et al. (1989) event list utilized the Shea & Smart (1990) compilation for 82 events during 1976–1986. Cliver et al. (1989) used a different, less restrictive set of criteria: (1) $\geq 10^{-3}$ protons $\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1}$ for 20–40 MeV protons and (2) evidence of velocity dispersion in the time-intensity profile, for 1980 February through 1985 January. Thus the latter set contained a few events not included in the former sets, and these weaker particle events generally associated with weaker X-ray events (e.g., for all flares greater than M1, 14% were selected on a less restrictive basis than the SESC criteria, but for all flares greater than X1, this excess was reduced to 2%).

Two sets of (overlapping) GHX rosters based on SMM HXRBS observations and covering the period 1980–1982 (Bai 1986; Cliver et al. 1986a) were available from the literature.

3.1. SEP-to-GHX Associations, 1980–1982

In 1980–1982 there were 28 SESC qualified (hereafter SESC) SEP events, 33 non-SESC SEP events, and 30 GHX events from the lists of Bai (1986) and Cliver et al. (1986a). Owing to the 50% duty cycle of SMM, 54% of the SEPs were associated with flares that occurred during SMM night. The SMM day-night incidence was distributed as follows: SESC SEPs—16 day, 12 night; non-SESC SEPs—12 day, 21 night.

Of the 18 SESC SEP flares that began during SMM day, 16 were also GHX flares. HXRBS observations of the two SESC SEP flares that were not identified as GHX flares were cut short because of the onset of spacecraft night. Thus it is possible that, had those HXRBS observations not been thwarted by spacecraft night, all 18 SESC SEP flares may have been GHX flares.

Fewer GHX matches were found in the smaller, non-SESC SEPs than in the more intense SESC events. SEP–GHX associations for smaller SEP events Cliver et al. (1989) occurred only rarely. Of 12 non-SESC SEPs occurring during spacecraft day,

only one matched a GHX. There is an apparent intensity threshold with respect to SEP and GHX coincidences; it is significant that all GHXs that coincided with large SEPs had high energy content: greater than 5×10^5 HXRBS counts.

3.2. GHX-to-SEP Associations, 1980–1982

GHX flares, viz. Tanaka's C-class (Tanaka et al. 1983), appear to be the least common of the flare classifications. Out of ~ 400 flares, Kosugi, Dennis, & Kai (1988) found that 13 were gradual, 338 were impulsive in hard X-rays, and the remainder were identified by the authors as having mostly weak hard X-rays accompanied by gradual-rise-and-fall (GRF) microwave bursts. In the present study, nine GHX flares (out of a total flare population of 960 registered by SESC for the same time span) were found in the range M1–M4, and 21 GHX flares (out of a total population of 240) were found in the range $\geq M5$. Of the 21 $\geq M5$ GHX flares, 17 were associated with SEPs (16 SESC, one non-SESC). Of the remaining five GHXs not associated with SEPs, four were situated at large eastern CMD and would not have been expected to produce an SEP observable at Earth. The magnitude and locations of those four far-eastern $\geq M5$ GHXs are shown in Table 3. Seven $\leq M5$ GHX flares were not associated with SEPs. This group of moderate (low M-class) flares were distributed over a wide range of CMDs: E99, E70, E39, E20, W52, W50, and W16.

Figure 5 shows the correspondence between SEPs and GHXs in the form of two parallel, filtered event-incidence matrices, SEP incidence on the left and GHX incidence on the right. The event-incidence matrices are simply representations of the aggregate SEP and GHX events occurring during a given epoch, in this case 1980–1982. The number of elements in the matrices is the sum of both types of event; each position within the matrix pertains to a specific date, which is the same for both matrices. The positions have no significance other than chronological order.

The figure is intended to demonstrate that filtering the original event incidence of 1980–1982 SEPs and GHXs through various criteria (e.g., SEP intensity, flare intensity, etc.) produces two nearly identical matrices. Event incidence for either SEPs or GHXs is indicated by an “x,” SESC-GHX event coincidence is indicated by an “x” in a circle, non-SESC-GHX coincidence is represented by an “x” in a square, and a dot indicates a position that has been vacated either in the original matrix or by filtering. The top panels show the original total incidence for both types of events; the middle panels show SESC SEPs on the left and more than M5 GHXs on the right. The bottom panels show the surviving SESC–SMM day SEPs on the left and the surviving greater than M5 and west of 60°E GHXs on the right, including the one non-SESC coincidence. In this sample for 1980–1982 there were 132 flares, mostly moderate to large (Fig. 3).

Table 4 is a contingency table from the number of SEPs and GHXs that met their respective acceptance criteria (seen in the bottom two panels of Fig. 5). The single false alarm (on 1981

TABLE 3
FOUR FAR-EASTERN GHX FLARES NOT ASSOCIATED WITH SEPs

Date	Soft X-Ray Class	Heliographic Longitude
1980 May 1	X3	E60
1981 Jan 25	M9	E90
1981 Feb 24	X1	E84
1981 Apr 14	M6	E73

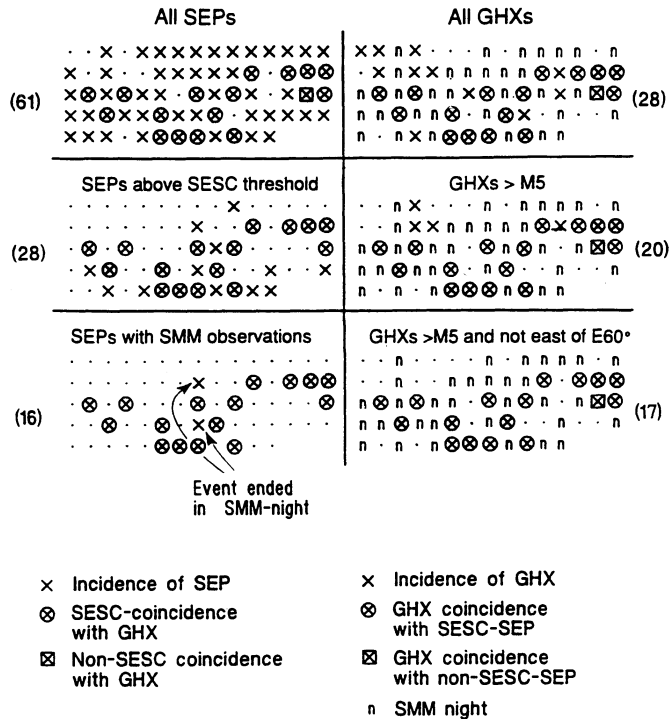


FIG. 5.—Parallel incidence matrices of SEP and GHX events, filtered through two additional criteria. SEP incidence matrices are shown on the left, GHX incidence on the right. Top panels depict the total incidence of each event type. Middle panels show the incidence after eliminating non-SESC events from SEPs and less than M5 flares from GHXs. The bottom panels show the surviving incidence matrices after eliminating SEP events occurring during *SMM* night and GHX flares occurring east of E60°. Each element of each matrix represents a specific date, which is common to both matrices. A dot means that the element was vacated by filtering or was vacant in the original form of that matrix. An “n” in the GHX column means that the SEP event occurred during *SMM* night.

November 14) was a GHX flare, which corresponded to an identified SEP (Cliver et al. 1989) that did not meet the SESC criteria. In all other respects the association between qualified SEPs and qualified GHXs in this sample was exact.

3.3. Summary of SEP–GHX Associations, 1980–1982

The principal results of the empirical associations between SEPs and GHXs for the 1980–82 period are the following:

SEP events meeting the SESC event criterion (≥ 10 particles $\text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1}$ of energy > 10 MeV for more than 15 minutes) almost always followed large GHX flares.

Less intense SEP events rarely associate with GHX flares.

Large GHX flares (soft X-ray class $\geq \text{M6}$) preceded SEP events at Earth, except in cases where the flare’s heliographic position was east of E60 CMD (i.e., where the flares were not magnetically well connected with Earth).

Small GHX flares (soft X-ray class $\lesssim \text{M2}$) rarely produce SEPs of sufficient intensity to meet the SESC threshold.

TABLE 4

CONTINGENCY TABLE FOR SEP–GHX EVENTS

SEP Events	Predicted SEPs	Did not predict SEPs
Occurred	16 (true)	0 (missed)
Did not occur	1 (false alarm)	115 (true)

4. SEPs VERSUS GRADUAL FLARES, IMPULSIVE FLARES, AND OTHER PHENOMENA

An early concept used in an attempt to explain the various observed traits of flares was that individual flares evolve on a timescale of minutes or tens of minutes. According to this model, the mechanism for accelerating particles shifts from a magnetically confined topology to a more open one. In X-rays this would manifest as an impulsive phase followed by a gradual or extended phase (Wild, Smera, & Weiss 1963). More recent models suggest that the observations are better explained by the existence of several flare types, each displaying some dominant form but also having some characteristics in common with the other types (Bai & Sturrock 1989). *Hinotori* investigators identified three principal flare types: compact, impulsive, and gradual, on the basis of their X-ray imagery, light curves, and spectra (Tanaka et al. 1983; Tsuneta et al. 1984). Some flares show evolutionary phases, changing from impulsive to gradual (Bai 1986)—but never the converse: gradual to impulsive. However, insofar as SEP flares and their associated phenomena are concerned, it is primarily the intrinsically “gradual” flare that shows the greatest consistency of association with these types of events (Cane & Stone 1984; Cane, McGuire, & von Rosenvinge 1986; Nonnast et al. 1982; Cliver et al. 1986a; Cliver et al. 1989; Cliver & Cane 1989; Kahler et al. 1984).

In the broadest interpretation, the term “gradual flares” applies to both hard and soft X-rays. It would be more useful to narrow the scope of flares that should qualify as SEP-flare candidates by specifying other necessary attributes. The commonly accepted meaning of the term gradual, as applied to flares, stems from the behavior of those flares in soft X-rays: their smoothness and their long duration. The problem with using a flare’s duration in soft X-rays as an unsupported means of SEP detection is that 70% of all gradual X-class soft X-ray flares are normal; i.e., nonproductive of SEPs (Cliver & Cane 1989).

Many other SEP attributes have been discovered, as have a number of equally useful signatures belonging to anticorrelative phenomena. The following subsections outline both the correlative and the anticorrelative attributes of SEPs, to illuminate their essentially binary nature and to facilitate later discussion of the role of temperature in SEP and non-SEP flares.

4.1. Flare Duration

Nonnast et al. (1982) studied 4–17 Å X-rays observed by *IMP 8* (1973–1977) and found that among flares with greater than 40 minute decays, 52% were associated with proton events; in contrast, in the case of flares with shorter decay times, only 14% were so associated. Their main conclusion, however, was that integrated X-ray flux (flux intensity times duration) was a better indicator than either maximum flux intensity or duration: greater than 1000 ergs cm^{-2} integrated flux yielded 86% probability of observable protons; greater than 100 ergs cm^{-2} to less than 1000 ergs cm^{-2} yielded 33% probability.

4.2. Decay Rate

The rate at which flares decay in soft X-rays may be more significant in the detection SEPs than the length of decay. The rate of rise to maximum, on the other hand, is not a useful detection parameter (Nonnast et al. 1982). Cliver & Cane

(1989) divided soft X-ray events into impulsive and gradual, based on e -folding decay times (t) from burst maximum: gradual $t > 10$ minutes; impulsive $t < 10$ minutes. Under this classification, 40% of X-class flares are impulsive (having 3% SEPs); of the remaining 60%, that are gradual, 30% are SEP-related. It is noted that Cliver & Cane (1989)'s SEP flux-intensity criterion is identical to SESC's (SESC now explicitly uses decay rate in its SEP forecast algorithm; Balch & Kunches 1986).

4.3. Energetic Protons and Electrons

The production of energetic protons is the focus of much interest in the study of gradual flares; i.e., these flares are recognized as being proton-rich. The relative electron versus proton abundance is customarily expressed by the ratio e/p . Cane et al. find that $e/p \sim 0.001 \rightarrow 0.08$ for LDEs (long duration event, soft X-ray flares), and $e/p \sim 0.02 \rightarrow 10$ for impulsive flares. Reames (1990) found impulsive flares to have consistently high electron-to-proton flux ratios, as observed directly or through type-III radio emission. Reames (1990) also studied ion and proton abundances. In this review he discusses that large proton events show elemental abundances similar to the corona and the solar wind, but anomalous ^3He and heavy ions were produced by impulsive flares. He suggests that protons are released for flares with access to open field lines, but energetic heavy ions emerge from impulsive flares and are accelerated, by stochastic interactions, from plasma waves generated near the site of impulsive flares.

4.4. Metric Radio Bursts and Interplanetary Shocks

Metric radio emission provides very good evidence that gradual and impulsive flares are the consequences of two distinct particle-acceleration mechanisms. Type III bursts are indicative of high-energy density, large electric fields, rapid acceleration, and relativistic electron beaming. Type II bursts are indicative of gradual acceleration, lower energy density, slow drifts, and extended shocks. Kahler (1982) determined that long-duration type II bursts (median time 23 minutes) were associated with proton flares but shorter duration bursts (median time 11 minutes) were not; therefore, a type II burst is not a sufficient condition for the occurrence of an interplanetary proton event. The same study indicated that decimetric or metric, stationary type IV bursts are required for most proton flares. Of impulsive events, 97% are associated with type III emission; 80% of LDEs are associated with type II emission, and 50% of LDEs are associated with interplanetary shocks (Cane et al. 1986). Kahler, Hildner, & van Holebeke (1978) found that protons are admitted into the interplanetary medium after being accelerated in shock fronts ahead of coronal mass ejections (CMEs). Kahler (1984) discovered a correlation between 4–22 MeV protons and CME speeds: "the faster the CME, the greater the peak 4–22 MeV flux." Wagner & McQueen (1983) proposed that an exciter shock arises from the impulsive flare; consequently, it follows the CME, and then travels through it at a higher velocity. Type II radio emission is then produced when the shock overtakes the principal density pileup. However, Dryer & Maxwell (1979) found that shocks tend to lead CMEs when flares occur singly.

4.5. Microwaves

Gradual flares in hard X-rays exhibit "microwave-rich" properties in comparison to impulsive IHX flares (Dennis

1988; Dennis & Schwartz 1989; Cliver et al. 1986a; Bai 1986; Bai & Sturrock 1989; and Kosugi & Kiplinger 1987). Chertok & Fomichev (1990) studied both microwave and meter wavelengths and determined that the intensity and frequency of microwave emission contained information on both the intensity and energy spectrum of protons. The microwave spectrum in the 3–9 GHz range is phenomenologically related to proton flux; i.e., higher proton intensity correlates with spectral peaks at low frequencies and, similarly, higher proton intensities correlate with softer proton spectra. (The latter result appears to be in conflict with Kiplinger 1993, who finds that higher proton intensities observed at Earth associate with hardening hard X-ray emission and, thus, harder electron spectra at the flare. If the proton spectra are indeed softer, it suggests a completely different acceleration mechanism.)

4.6. Heliographic Longitude

Significant evidence indicates that SEPs sometimes emerge directly from flares, sometimes are the result of shock acceleration, and sometimes come from a combination of the two (Cane, Reames, & von Rosenvinge 1988; Chertok & Fomichev 1990). SEPs display an organization with respect to longitude, and the controlling agent is the interplanetary shock: eastern events are characterized by long delays to maximum (suggesting a shock origin). Particles magnetically well-connected to Earth propagate quickly, by diffusive transport, from heliographic longitudes $W10^\circ$ – $W90^\circ$. Interplanetary shocks are important generators of particles not magnetically connected to the source. Cane et al. (1988) found that the "vast majority of events from eastern regions" were followed by interplanetary shocks. Chertok & Fomichev (1990), observing microwaves, found that high-intensity soft proton fluxes came from western sources.

Gradual flares generally produce enhanced proton fluxes, either directly or by shock acceleration, in western longitudes; for flares sited in eastern longitudes, it is probable that all or most proton events result from interplanetary shocks. This scenario is based primarily on the work of Cane et al. (1988), who found that the majority of proton events west of $W20^\circ$ are not associated with shocks, and that proton intensities and shock strengths are generally found to be larger in the eastern hemisphere than in the western hemisphere. Cane et al. (1986) also found that most impulsive events with known flares originate west of $W10^\circ$.

4.7. Coronal Mass Ejections

Kahler (1992) has reviewed the evidence for the long-held belief that flares are the principal source of mass ejections from the Sun in the form of CMEs; he has contrasted these findings with more recent evidence, which indicates that the converse is actually the case: CMEs are the original source of energy, and flares are only secondary phenomena. Arguments in favor of a dominant role for CMEs derive from three leading diagnostics: timing, energetics, and spatiality. Specifically, the onset time of a CME precedes that of the associated flare, the CME has more energy than the flare, and the CME is vastly larger in volume than the flare.

The association between SEPs and CMEs was also the subject of an earlier study (Kahler et al. 1984). That study found that (1) there was "a high but not perfect association of prompt proton events with CMEs;" (2) front-side proton events consistently associated with H α flares; (3) not all CMEs

associated with proton events, but those that did had looplike or fan structures (CMEs that did not associate with proton events had spikelike jets and irregular structure); (4) CME speeds correlated with proton flux intensity; and (5) CME occurrence correlated with X-ray event duration but not with X-ray event intensity.

Two of Kahler's main conclusions regarding the relationship of CMEs and SEPs were that (1) "a CME may be a necessary requirement for the occurrence of a flare proton event," and (2) "the CME acts as a driver to set up a coronal shock in which protons are accelerated."

Cliver et al. (1986a), in a study of 10 gradual hard X-ray events, found that nine of these events were associated with CMEs and, further, that the CMEs appeared to precede the hard X-ray bursts.

5. THE PHYSICAL BASIS FOR GRADUAL HARD X-RAY FLARES AND SEPS

SEPs frequently associate with a type of flare characterized by smooth, long-duration light curves in both soft and hard X-rays. This flare type exhibits other distinguishing features such as great height, hardening spectra, microwave-rich emission, etc. In contrast, SEPs show poor correlation with a more common flare type identified by its impulsive behavior in both soft and hard X-rays. Furthermore, SEPs that do not emerge directly from the former (gradual) flare type tend to be generated by interplanetary shocks that often result from or are connected with that type of flare. Indeed, the attributes of SEPs and their associations seem to be generated by the relationship that each attribute bears to the gradual X-ray flare species.

GHX flares may be a subclass of a larger group of gradual flares that are known primarily for their long-duration soft X-ray characteristics. GHX flares are recognized as a separate class of flares because of their distinctive hard X-ray signatures, which differ significantly from those of the more common IHX flares. GHX flares often exhibit traits in common with gradual soft X-ray flares, but, as we have noted, only a very small number of that type of flare has been identified thus far. During the period of this study, 1980–1982, there were 1660 flares greater than M1 and 101 flares $\geq$ X1. Thus, from the collective GHX rosters of Bai (1986) and Cliver et al. (1986a) 1.8% of greater than M1 flares were GHX and 15% of greater than X1 were GHX. However, these percentages probably underestimate the actual number of GHX flares by a factor of 2 or greater owing to SMM's 50% duty cycle and because Bai (1986) used a HXRBS count-rate threshold of 1000 counts s^{-1} , and it is likely that many weaker GHX flares fell below this threshold. Nonetheless, these low percentages contrast with the abundance (60%) of X-class gradual soft X-ray flares identified by Cliver & Cane (1989). We must assume that most gradual soft X-ray flares are not GHX flares but may, in fact, be normal, impulsive flares in hard X-rays. This distinction is important because of the very high correlation of GHX flares with SEPs, CMEs, and interplanetary shocks.

GHX light curves, as the name suggests, are smooth and of long duration (>10 minutes). IHX light curves, on the other hand, are spiky and of short duration (~ 2 minutes). GHX spectral indices are typically small ($\gamma < 4.5$). However, the most distinctive hard X-ray signature is seen in the time development of each flare type. GHX spectra evolve in a pattern of soft $\rightarrow$ hard $\rightarrow$ harder, whereas IHX spectra evolve soft $\rightarrow$ hard $\rightarrow$ soft (Bai & Sturrock 1989; Kosugi et al. 1988).

Some early analysis of GHX flares suggested that highly

energized particles were a result of secondary accelerations due to shocks (Frost & Dennis 1971; Svestka 1976). More recent evidence indicates that shocks and CMEs may erupt *before* the flare itself (Cliver et al. 1986a; Simnett & Harrison 1985; Harrison et al. 1985). Tsuneta et al. (1984), using *Hinotori* observations of the flare of 1981 May 13, concluded that an acceleration agent for the gradual hard X-ray burst could not have been a type II shock since no type II radio burst was observed. However, this finding does not necessarily mean that no shock occurred; i.e., even if a shock had been present, a type II burst may not have been generated if the angle between the shock front and the *B* before the shock was too small ($< 80^\circ$) (Holman & Pesses 1983). Cliver et al. (1986a) argue against the shock hypothesis for this type of flare, and in favor of a late developing acceleration process requiring electron trapping in large loop systems.

The concept of prolonged particle acceleration in postflare loops, characteristic of spectral hardening in GHX flares, has also been advanced by several authors using either *Hinotori* or *SMM* X-ray observations (Takakura, Tanaka, & Hiei 1984; Ohki et al. 1983; Bai 1986; Kosugi et al. 1988; Dennis 1988; Dennis & Schwartz 1989). The concept of electron trapping in low-density, large-volume high loops with weak magnetic fields conforms with many of the above described attributes of SEP flares.

Spectral hardening can also be explained in terms of propagation effects in a collision-dominated trap as described by Ryan (1986). In this model, collisions of accelerated particles with ambient nuclei produce hard X-rays and γ -radiation through bremsstrahlung or nuclear excitation. As a result of this mode of trapping, the hard X-ray emission becomes less impulsive, the peak of the emission is retarded with respect to particle production, and the emission spectra harden with time—all attributes of the gradual hard X-ray burst associated with the production of SEPs.

Finally, it must be noted that large SEP events (meeting SESC criterion) are occasionally associated with relatively weak flares (Cliver et al. 1983) and on other occasions weaker SEP events occur in association with disappearing filament events rather than with flares (Kahler et al. 1986; Sanahuja et al. 1986, 1991). The absence of strong impulsive phases in these events and their associations with fast coronal mass ejections and coronal/planetary shocks led Cliver et al. (1983) and Kahler et al. (1986) to argue that the key ingredient for SEP acceleration in these events, and probably other classic "big flares" as well, was a CME-driven shock wave. However, since both the weak flares discussed by Cliver et al. (1983) and the filament disappearances discussed by Kahler et al. (1986) and Sanahuja et al. (1986, 1991) were long-duration events involving field line opening by CMEs and subsequent reconnections, the possibility remains that SEP acceleration involving low-intensity GHX bursts can occur in postflare magnetic loops in these events.

6. CONCLUSIONS

The main empirical finding of this study is that two complementary types of flares correlate strongly with solar energetic proton events observed in Earth's magnetosphere and in interplanetary space: (1) anomalous low flare temperatures for moderate (M-class) soft X-ray flares; (2) gradual hard X-ray characteristics for more intense ($\geq$ M5) flares.

The two flare types overlap at upper M-class and low X-class flare intensities, but each has clear dominance at its respective end of the flare-intensity scale.

The empirical results evoke a number of questions:

1. Why are low-intensity SEP flares generally cooler than normal flares?
2. Why is the temperature distribution for intense SEP flares so broad; i.e., why are there also high-temperature SEP flares?
3. Why is the GHX-SEP correlation less pronounced for weak flares?
4. Are low-temperature flares that associate with SEPs generically of the same flare type as those that are GHXs in hard X-rays?
5. In the final analysis, why do low-temperature flares and GHX flares produce or, by some chain of events, cause energetic protons in interplanetary space?

The following paragraphs attempt to provide partial answers to the above questions.

1. The problem of why low-intensity SEP flares are cooler than normal flares might be more easily addressed by inverting the question; i.e. why are low-intensity normal flares hotter? Normal flares are hotter because they occur at lower altitude, in denser plasmas, and in stronger, more complex magnetic fields. Tanaka (1987) concluded that high-temperature flares have higher densities ($n = 10^{11} - 10^{12} \text{ cm}^{-3}$). He inferred this from the observed fact that high-temperature impulsive flares decay more rapidly than do their cooler counterparts, a condition suggestive of high densities. Another reason for high temperatures in normal, low-lying flares may be that the magnetic topologies are closed; i.e., particles accelerated by the flare remain trapped, return to the denser atmosphere, and release heat in the collisional loss process.

2. The problem of the broad temperature distribution of intense SEP flares is more difficult; many of the above arguments used to explain high temperatures in low-intensity, low-lying flares would not apply to SEP flares if the latter occur in high-altitude, tenuous plasmas and in weak magnetic fields. In the "big-flare syndrome" (Kahler 1982), extreme flares produce interplanetary protons simply by overcoming the bonds of magnetic containment. Such flares could originate in low-lying, dense plasmas with large magnetic fields, and thus would have high temperatures. A disproportionate number of (relatively) low-temperature GHXs for intense (X-class) flares and a disproportionate number of high-temperature non-GHX flares would strongly suggest that the big-flare syndrome was responsible for most high-temperature SEP flares.

3. SEP-GHX coincidence for weak SEPs may be small as a result of a selection effect; it is difficult to identify the gradual-burst signature in low-intensity SEP flares. The countervailing argument for unmatched GHX flares is that weak SEPs (owing to a lack of magnetic connectivity or because of insufficiently sensitive particle detectors) may not produce an observable effect at Earth.

4. Despite the low correlation between SEPs and GHXs in weak flares, the underlying causes of low-temperature SEP flares and GHX flares are sufficiently similar to suggest that they are generically related flare types. The temperature analysis of GHX flares (§ 2.3 above) demonstrated that GHX flares observed in soft X-rays tend to have anomalous low temperatures just as SEP flares do. Furthermore, many SEP-GHX coincidences have been observed in intense flares, and often these flares have (relatively) low temperatures. If low temperatures in flares result from low densities, weak fields, and open magnetic topologies, (the same attributes that belong to GHX flares), then the two phenomena appear to be related and may spring from the same source.

5. Section 5 described a number of outstanding traits of GHX flares. In particular, electron trapping at low density appears to address, in part, the issue of progressive spectral hardening and the concomitant excitation of primarily type IV metric radio waves and microwaves. Because the particles are close to magnetic formations susceptible to reconnection and reformation into "open" field topologies, it is possible that they have access to escape routes on interplanetary field lines.

The above theory, in which the acceleration of interplanetary particles is attributed to a fundamentally flarelike process (albeit one that occurs in the late stages of a rare species of flare) appears to have diminishing credibility in the face of new evidence that CMEs, not flares, are the principal drivers of SEPs and SEP-related flares (Kahler 1992). The alternative to energization by reconnection in large postflare loops is shock acceleration in front of the advancing CME (Kahler et al. 1984); however, the progressive spectral hardening in hard X-rays, shown to be characteristic of virtually all hard X-rays contained in the sample herein, seems to suggest a postflare loop site rather than a shock front. Furthermore, the observations that successive peaks in microwave bursts trend to lower frequencies suggest that "reconnection (leading to acceleration) occurs intermittently at greater heights and, therefore, within weaker magnetic fields" (Cliver et al. 1986b). The anomalous low temperatures found in many moderate to low-intensity flares are not inconsistent with either a CME driver or postflare loop acceleration.

Thus, at this time there are two competing theories for acceleration of SEPs-flare versus CMEs, with recent evidence seeming to favor the CME side (Kahler 1992). However, the high degree of association that we find between the low-temperature flares and GHX bursts and SEP events suggests a close physical link between the particles accelerated and interacting at the Sun and those that escape to the interplanetary medium. The picture we advocate here, particle acceleration in postflare loop systems, presumably via reconnection, has previously been proposed by Svestka, Martin, & Kopp (1980), Cliver (1983), Cliver et al. (1986a) and Chertok & Fomichev (1990) although none specifically addressed a link between low-temperature flares and GHX bursts and SEP acceleration.

One way to verify a generic relationship between low-temperature flares and GHX flares would be through X-ray imagery of the corona. Many investigators already recognize that GHX flares occur in large, high, tenuous, weak-field postflare loops (§ 5). Coronal X-ray imagery would be a valuable aid in discovering size, height, and morphology of low-temperature flares.

Very recent work by Kiplinger (1993) using HXRBS data collected during the whole of *SMM*'s main operational lifetime, 1980-1989, has demonstrated that progressively hardening spectra in hard X-rays provide the principal identifying signature for GHX flares. Spectral hardening as a means for GHX identification applies not only to the decay phase in hard X-rays but to late-occurring individual bursts as well. Either signature is sufficient to classify a flare as being precursor to the production of interplanetary protons. The high correlation between SEPs and spectrally hardening flares found by Kiplinger (1993) suggests that this attribute may be primary among exploitable observables from future Sun-monitoring space craft, a part of whose mission is to detect and forecast important particle events.

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